

TESTING GRAVITY ON LARGE SCALES: THE SKEWNESS OF THE GALAXY DISTRIBUTION AT $z \sim 1$

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We study the evolution of the low-order moments of the galaxy overdensity distribution over the redshift interval $0.7 < z < 1.5$. We find that the variance and the normalized skewness evolve over this redshift interval in a way that is remarkably consistent with predictions of first- and second-order perturbation theory. This finding confirms the standard gravitational instability paradigm over nearly 9 Gyrs of cosmic time and demonstrates the importance of accounting for the non-linear component of galaxy biasing to avoid disagreement between theory and observations.

1 Introduction

Determining the value of the parameters entering into the Friedmann-Robertson-Walker model is a classical problem of cosmology which has recently been addressed with unprecedented accuracy¹. A large variety of independent data are suggestive of a new physical scenario, rich in philosophical implications: it seems that we live in a universe where ordinary baryonic matter is a minority ($\sim 1/6$) of all matter, where matter itself is a minority ($\sim 1/4$) of all energy, where geometry is spatially flat and the metric expansion is presently accelerated. However, to make sense of these measurements, a mysterious dark energy component has been added to an already elusive ingredient, *i.e.* dark matter.

Since fixing model parameters is not measuring and, as such, it can hardly give us insight into the physical nature of the phenomenon investigated, it is critical to understand whether

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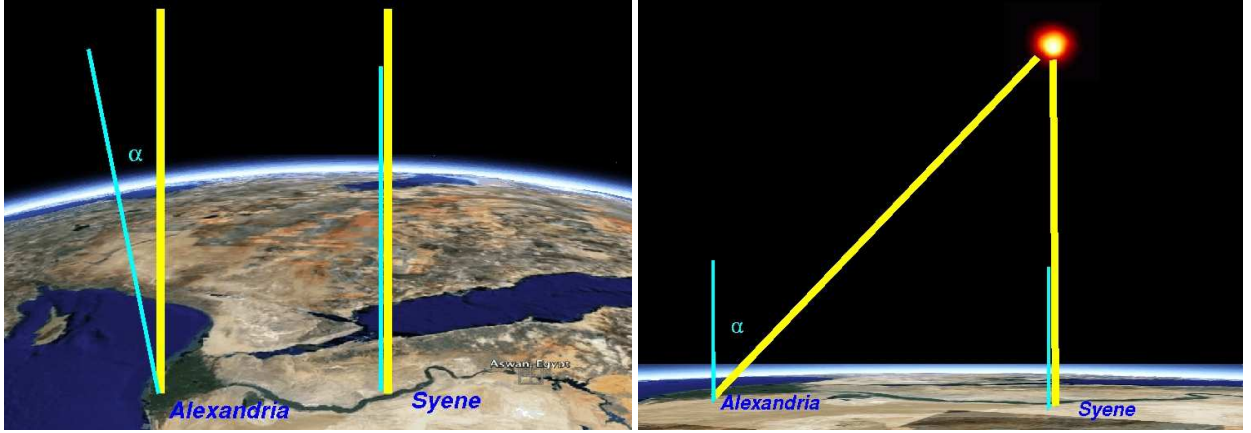


Figure 1: World models of Eratosthenes (*left*) and Anaxagoras (*right*). Note that the same astronomical observations were available to the two Greek scholar *i.e.* that at noon, the sun rays were differently inclined in Syene and Alexandria (here only pictorially represented) the day of the summer solstice. But data do not speak by themselves; rather they must be interpreted within a theoretical framework. Without an independent test of the hypothesis that the earth is spherical, Eratosthenes' is not a physical measure but a model-dependent parameter estimation.

what we interpret as new cosmic components is rather the smoking gun of the failure of our theoretical model on large cosmological scales^{2,3,4}.

An example will better illustrate how important is testing the hypotheses underlying the standard model of cosmology as well as the soundness of the assumptions implicit in cosmological “measurements”. Eratosthenes is remembered for a technique he introduced which enabled him to compute the first reliable determination of the radius of the earth. He interpreted available data (the different inclination angle of sun rays at noon in Syene and Alexandria the day of summer solstice) assuming that the earth *is* spherical, that the two towns are on the same meridian and that the sun is far enough that its rays are almost perfectly parallel (see Fig. 1). On the basis of these hypotheses he estimated the radius of the earth with a precision greater than the accuracy currently attained in measuring dark energy. What is not often emphasized is that these same ‘high quality’ data were available to another Greek scholar, Anaxagoras who lived nearly two centuries before. By interpreting them assuming that the earth *is* flat and that the different inclination of the rays is due to the sun proximity (see right panel of Fig 1), he concluded, with spectacular precision, that the sun is as big as the Peloponnese.

The picture in which gravity, as described by general relativity, is the engine driving cosmic growth is generally referred to as the gravitational instability paradigm (GIP). However plausible it may seem, it is critical to test its validity. In the local universe the GIP paradigm has been shown to make sense of a vast amount of independent observations on different spatial scales from galaxies to superclusters of galaxies^{5,6}. Deep redshift surveys now allow us to test whether the predictions of this assumption are also valid at earlier epochs⁷.

We test the role of gravity in shaping density inhomogeneities by using three-dimensional maps of the distribution of visible matter revealed by the VIMOS-VLT Deep Survey^{8,7} over the large redshift baseline $0 < z < 1.5$ (see Massey et al.⁹ for three dimensional cartography of mass overdensities in the COSMOS field).

We explore the mechanisms governing this growth by comparing the time evolution of the low-order moments of the galaxy PDF, (*i.e.* the *variance* amplitude $\langle \delta_g^2 \rangle$ and the *normalized skewness* $S_3 = \langle \delta_g^3 \rangle_c / \langle \delta_g^2 \rangle_c^2$) with the corresponding quantity theoretically predicted for matter fluctuations in the linear and semi-linear perturbation regime. This provides a test of GIP-specific predictions at as-yet unexplored epochs that are intermediate between the present era and the time of decoupling. Knowledge of the precise growth history of density inhomom-

geneities provides also a way to test the theory of gravitation¹⁰.

In addition to the statistical approach presented in this paper, we have recently addressed this same issue also from a dynamical point of view. We have used linear redshift-space distortions in the VVDS-*Wide* data to measure the growth rate of matter fluctuations at $z \sim 0.8$ ¹¹. This approach offers promising prospects for determining the cause of cosmic acceleration in the near future¹².

2 A cosmographical tour up to $z = 1.5$

By using the VVDS data we have reconstructed, for the first time, the three-dimensional map of large-scale galaxy fluctuations to $z = 1.5$. The $I \leq 24$ sample is characterized by an effective mean inter-particle separation of ($\langle r \rangle \sim 5.1 h^{-1}\text{Mpc}$) in the redshift range $0 < z < 1.5$. For comparison, this sampling is better (denser) than the early CfA1 survey ($\langle r \rangle \sim 5.5 h^{-1}\text{Mpc}$) used by Davis & Huchra¹³ to reconstruct the 3D density field of the local Universe (*i.e.* out to $\sim 80 h^{-1}\text{Mpc}$). Also, at the median depth of the VVDS survey, *i.e.* in the redshift interval $0.7 < z < 0.8$, the mean inter-particle separation is $4.4 h^{-1}\text{Mpc}$, a value nearly equal to the 2dFGRS at its median depth.

The recovered galaxy overdensity field is presented in Fig. 2. Fluctuations have been smoothed on a scale $R = 2h^{-1}\text{Mpc}$. Only density contrasts with signal-to-noise ratio $S/N > 2$ are shown.

A remarkable feature of this “*geographical*” exploration of the Universe at early cosmic epochs is the abundance of large-scale structures similar in density contrast and size (at least in one direction) to those observed by local surveys. In particular, it is tempting to identify qualitatively a few filament-like density enhancements bridging more condensed structures along the line of sight, although the survey transverse size is still too small to fully sample their extent. Nevertheless, it is interesting to notice that these apparently one-dimensional structures remain coherent over scales $\sim 100h^{-1}\text{Mpc}$, separating low-density regions of similar size. Figs. 2 and 3 visually confirm that the familiar web pattern observed in the local Universe is not a present-day transient phase of the galaxy spatial organization but it is already well-defined at ~ 1.5 when the Universe was $\sim 30\%$ its present age. This implies that large-scale features of the galaxy distribution essentially reflects the long-wavelength modes of the initial power spectrum, in agreement with theoretical predictions of the CDM hierarchical scenario. Numerical simulations of large scale structure formation in fact show that the present-day web of filaments and walls is actually present when the universe was in embryonic form in the overdensity pattern of the initial fluctuations, with subsequent linear and non-linear gravitational dynamics just sharpening its features^{14 15}.

The limited angular size of the survey is exemplified by a dense “wall” at $z = 0.97$ that stretches across the whole survey solid angle (0.7×0.7 deg) (see Fig. 3). This two-dimensional structure is coherent over more than $\sim 30h^{-1}\text{Mpc}$ (comoving) in the transverse direction, is only $\sim 10h^{-1}\text{Mpc}$ thick along the line of sight, and has a mean overdensity $\delta_g = 2.4 \pm 0.3$. This makes it similar to the largest and rarest structures observed in the local Universe, such as the Shapley concentration¹⁶. By applying a Voronoy-Delaunay cluster finding code¹⁷, we find 10 distinct groups in this structure, with between 5 and 12 galaxy members each (down to the limiting magnitude $I=24$), for a total of 164 galaxies. If one considers the evolution of *mass* fluctuations in the standard ΛCDM model, the probability of finding a structure with similar *mass* overdensity at such early times ($0.9 < z < 1$) would be nearly 4 times smaller than today: one such *mass fluctuation* would be expected in a volume of $\sim 3 \cdot 10^6 h^{-3}\text{Mpc}^3$, *i.e.* nearly 5 times larger than our surveyed volume up to $z \sim 1$. In fact, as shown by Marinoni et al 2005¹⁹ finding such a *galaxy* overdensity is not so unusual: it is clear evidence that the *biasing* between galaxies and matter at these epochs is higher than today. This makes fluctuations in the galaxy

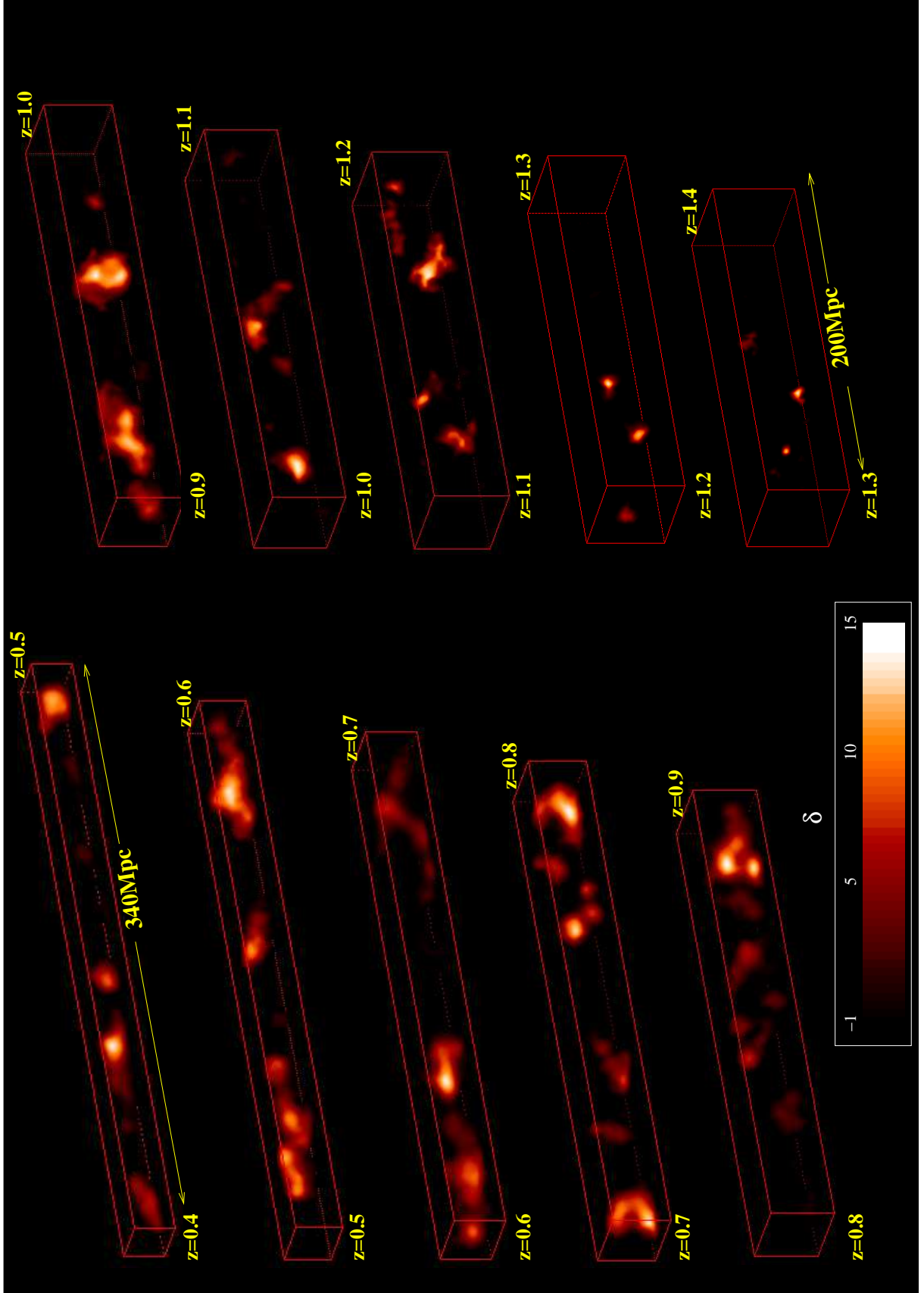


Figure 2: The reconstructed density field for $0.4 < z < 1.4$, as traced by the galaxy distribution in the VVDS-Deep redshift survey to $I \leq 24$. This figure preserves the correct aspect ratio between transverse and radial dimensions. The mean inter-galaxy separation of this sample at the typical depth of the VVDS ($z = 0.75$) is $4.6h^{-1}\text{Mpc}$, comparable to local redshift surveys as the 2dFGRS. The galaxy density distribution has been smoothed using a 3D Gaussian window of radius $R = 2h^{-1}\text{Mpc}$ and noise has been filtered away using a Wiener filtering technique. Only fluctuations above a signal-to-noise threshold of 2 are shown. The accuracy and robustness of the reconstruction

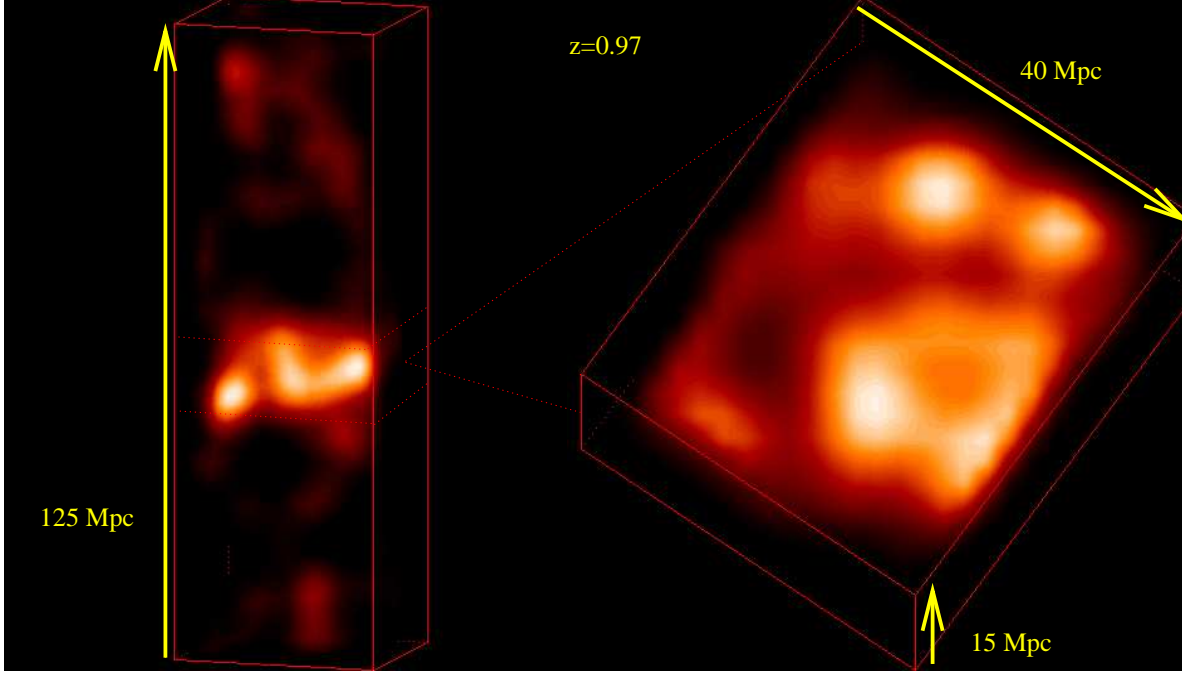


Figure 3: Density distribution and properties of a large-scale planar structure at $z = 0.97$, that completely fills the VVDS-02h field-of-view.

distribution to be highly enhanced with respect to those in the mass.

3 Testing gravitational instability with the low-order moments of the PDF

We have used the density maps presented in Fig. 2. to reconstruct the Probability Distribution Function of galaxy fluctuations on large cosmological scales⁷ and to study the evolution of its low-order statistical moments, *i.e.* variance and skewness.

To facilitate comparison between local and high redshift results we estimate these quantities for a volume-limited sample of VVDS galaxies with $M_B \leq -20 + 5 \log h$ (*i.e.* for a sample of test particles with median luminosity $\sim 2L_*$). Moreover, since in perturbation theory higher order cumulants are predicted to be a function of the variance, we will always consider in the following the normalized skewness $S_3 = \langle \delta_g^3 \rangle_c / \sigma^4$.

Fig. 4 shows the evolution of the *rms* fluctuation and the normalized skewness on a scale $R = 10h^{-1}\text{Mpc}$, as measured from the VVDS volume-limited sub-samples. Errors have been computed using the 50 fully-realistic mock catalogs of VVDS-Deep discussed in Pollo et al. (2005). This allows us to include an estimate of the contribution of cosmic variance, which represents the most significant term in our error budget.

The top panel of Fig. 4 shows that the square-root of the variance, which measures the r.m.s. amplitude of fluctuations in galaxy counts, is with good approximation constant over the full redshift baseline investigated: in redshift space, the mean value of σ_g for our volume-limited galaxy samples is 0.78 ± 0.09 for $0.7 < z < 1.5$. A similar, nearly constant value is also consistent with the value estimated at $z \sim 0.15$ from the 2dF galaxy redshift survey²⁰ that is also reported in same figure. This means that over nearly 2/3 of the age of the Universe the

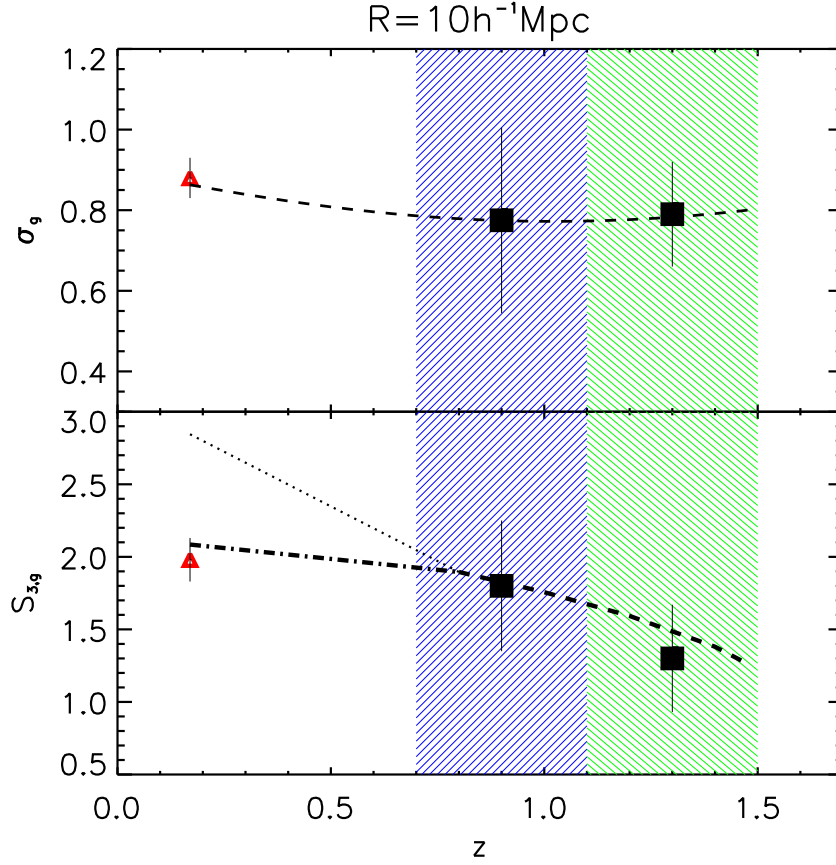


Figure 4: Evolution of the *r.m.s* deviation (top) and skewness (bottom) of the PDF of galaxy fluctuations on a scale $R = 10h^{-1}\text{Mpc}$. The filled squares correspond to two volume-limited samples from the VVDS with $M_B < -20 + 5\log h$ covering the redshift intervals indicated by the shaded regions. Triangles correspond to the 2dFGRS measurements at $z \simeq 0.15$ (Croton et al. 2005), from a sample including similarly bright galaxies. Error bars give 68% confidence errors, and, in the case of VVDS measurements, include the contribution from cosmic variance. The dashed lines in both panels show the theoretical predictions for the evolution of the variance (Eq. 1) and skewness (Eq. 3) inferred using VVDS measurement of biasing (Marinoni et al. 2005). Predictions for the skewness (based on the $(b_1(z), b_2(z))$ measurements in the redshift range $0.7 < z < 1.5$ have been extrapolated to $z \sim 0$ using the local (2dFGRS) biasing measurements of Verde et al. 2002 (linear bias, dotted line) and of Gaztañaga et al. 2005 (quadratic bias with $b_2/b_1 = -0.34$, dot-dashed line).

observed fluctuations in the galaxy distribution look almost as frozen, despite the underlying gravitational growth of mass fluctuations. This quantifies the visual impression we had from Fig. 2, that the distribution of galaxies is as inhomogeneous at $z \sim 1$ as it is today.

The third moment, which measures asymmetries between under- and over-dense regions, indicates that the galaxy density field was non-Gaussian on large scales ($10 h^{-1}\text{Mpc}$) even at these remote epochs ($\sim 4\sigma$ detection). In particular we find indication for an increase of the normalized skewness with cosmic time, when comparing the VVDS values to the local measurement by 2dFGRS.

4 Comparison with Theoretical Expectations

Marinoni et al. ¹⁹ used the same VVDS sample of luminous galaxies to measure the cosmological biasing between matter and galaxy distributions¹⁹. The key result from that analysis was that galaxy biasing is non-linear on scales $R = 10h^{-1}\text{Mpc}$. and increasing with redshift.

Using this ingredient we can now contrast the observed redshift scaling of the low-order statistical moments of the galaxy PDF against the theoretical predictions for the evolution of the variance and skewness of the matter density field. Our goal is to test the consistency of some general predictions of the GIP.

Using linear perturbation theory, the scaling of the *rms* of galaxy density fluctuations is

$$\sigma_g(z) \sim b_1(z)D(z)p(z)\sigma(0) \quad , \quad (1)$$

where b_1 is the linear term of the biasing function⁷, $D(z)$ is the linear growth factor of density fluctuations, $p(z)$ is the redshift-dependent Kaiser correction which takes into account the average contribution of the linear redshift distortions induced by peculiar velocities²³, and $\sigma(0)$ is the present-day *rms* of the mass density fluctuations.

In a Universe in which primordial density fluctuations were Gaussian, the non-linear nature of gravitational dynamics leads to the emergence of a non-trivial skewness of the local density PDF. According to predictions of the non-linear, second-order perturbation theory, the skewness of the mass distribution is approximately independent of time, scale, density, or geometry of the cosmological model. Assuming that its evolution only depends on the hypothesis that the initial fluctuations are small and quasi-Gaussian and that they grow via gravitational clustering one derives that, in redshift-distorted space²⁴

$$S_3 \sim \frac{35.2}{7} - 1.15(n + 3) \quad (2)$$

where n is the effective slope of the power spectrum on the scales of interest (i.e. in our case, since $R = 10h^{-1}\text{Mpc}$, n is approximately given by -1.2). Substituting the relevant expansion terms of the biasing function, the evolution of the observed skewness is given by Fry & Gaztañaga 1993²⁵

$$S_{3,g} \sim b_1(z)^{-1} \left[S_3 + 3 \frac{b_2(z)}{b_1(z)} \right]. \quad (3)$$

The curves in both panels of Fig. 4 show that equations (1) and (3) reproduce extremely well the evolution of variance and skewness observed within the VVDS. Concerning the local measurements from 2dFGRS, the predicted scaling for the skewness continues to show very good agreement if, even locally, biasing is non-linear as we measured at high redshift ($\langle \frac{b_2}{b_1} \rangle = -0.19 \pm 0.04$) over the redshift range $0.7 < z < 1.5$) and as confirmed by the analysis of Gaztañaga et al.²¹ of the 2dFGRS sample ($b_2/b_1 = -0.34$) These results provide an indication of the consistency, at $z = 1$, of some constitutive elements of the standard picture of gravitational instability from Gaussian initial conditions. The value of $S_{3,g}$, however, cannot be consistent with GIP predictions if in the local universe the simple linear biasing measurement of Verde et al.²² (*i.e.* $b_2 = 0$) is adopted.

The results we have presented provide the first direct evidence at $z \sim 1$ for the consistency of the GIP hypothesis as described in the framework of general relativity. The standard theory of structure formation via gravitational instability successfully explains the present day statistics (e.g. Tegmark et al. 2006) and dynamics (e.g. Peacock et al. 2001) of large scale structures. We have shown that observations are fully consistent with these predictions over the entire redshift baseline $0 < z < 1.5$ only if the small (10%) yet crucial non-linearities measured in the biasing relation are taken into account.

References

1. Dunkley, J., 2008, ApJS submitted, arXiv:0803.0586

2. Dvali, G., Gabadadze, G., Porrati, M., 2000, PhLB, 484, 129
3. Amendola, L, Polarski, D. & Tsujikawa, S., 2007, Phys.Rev. Lett, 98, 1302
4. Buzzi, A. Marinoni, C., Colafrancesco, S., 2008, JCAP, 11, 1
5. Peacock, J. A., 2001, Nature, 410, 169
6. Tegmark, M., et al. 2006, Phys. Rev. D, 74, 123507
7. Marinoni, C., et al. (the VVDS Team) 2008, A&A 487, 7
8. Le Fèvre, O., et al. (the VVDS Team) 2005, A&A, 439, 845
9. Massey, R., et al. 2007, Nature, 445, 286
10. Linder, E. V., 2005, PhRvD, 72, 3529
11. Guzzo, L., et al. (the VVDS team) 2008, Nature, 451, 541
12. Linder, E. V., 2007, A&A in press, arXiv:0709.1113
13. Davis, M., & Huchra, J., 1981, ApJ, 254, 437
14. Bond, J. R., et al. 1996, Nature, 380, 603
15. Springel, W., et al. 2005, Nature, 435, 629
16. Scaramella, R., et al. 1989, Nature, 338, 562
17. Marinoni, C., et al. 2002, ApJ, 580, 122
18. Pollo, A., et al. (the VVDS team) 2005, A&A, 439, 887
19. Marinoni, C., et al. (the VVDS team) 2005, A&A, 442, 801
20. Croton, D. J., et al. 2004, MNRAS, 352, 1232
21. Gaztañaga, E., et al. 2005, MNRAS, 364, 620
22. Verde, L., et al. 2002, MNRAS, 335, 432
23. Kaiser, N., 1987, MNRAS, 227, 1
24. Hivon, R., et al. 1995, A&A, 298, 643
25. Fry, J. N., & Gaztañaga, E., 1993, ApJ, 413, 447